Supplemental materials

This supplemental document is divided into two parts. Sect. S1 provides supplemental figures for the main text. Sect S2 should be read as building advice for recreating the system, based on “in hindsight” experience. In addition to this document, we provide the templates, dimensional drawings, and 3D models that were used in the construction process, in the attached .zip file. These construction files are discussed in Sect. S2.

S1 Supplemental figures

S1.1 Profiling arm tipping frame

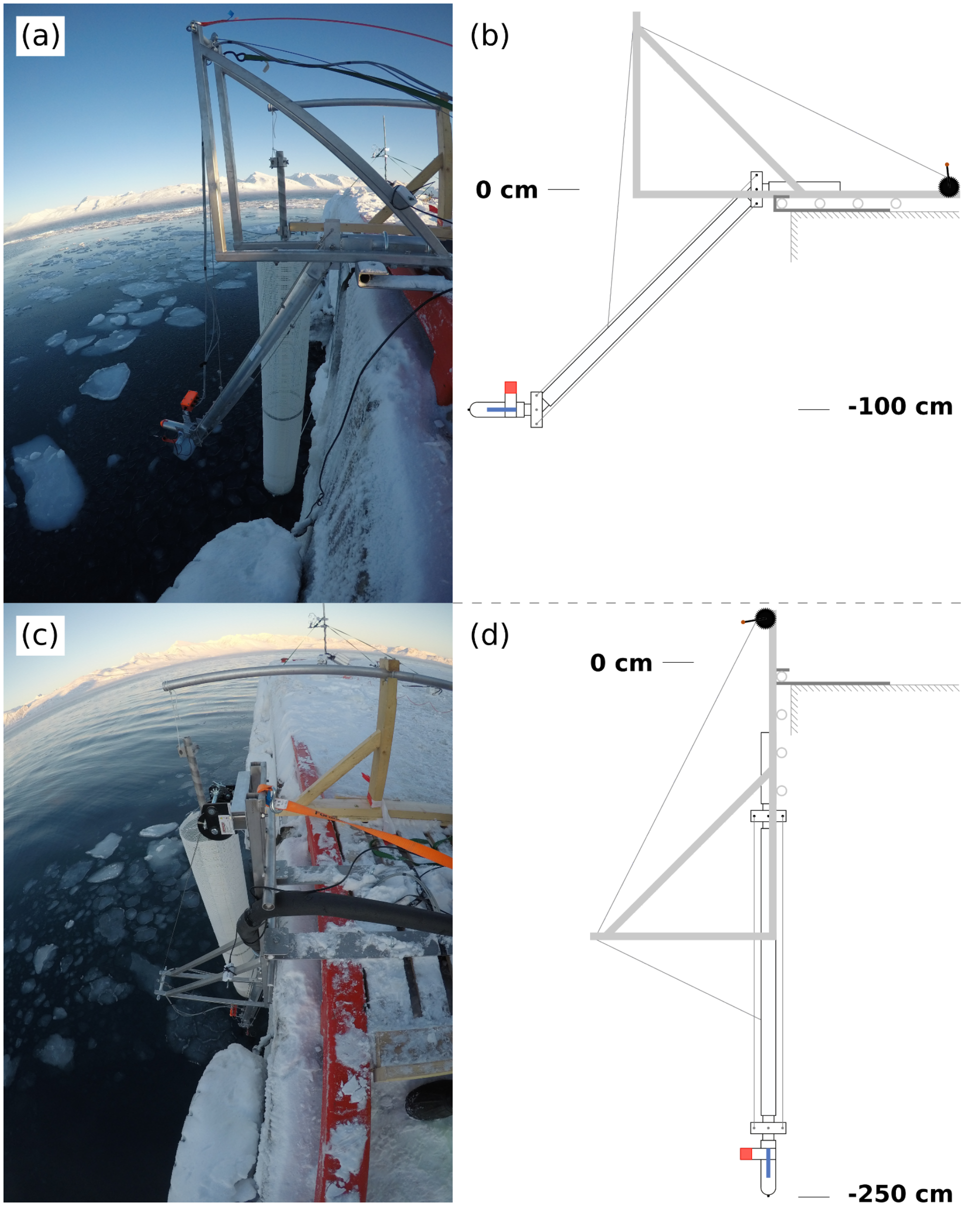

Figure S1. The profiling arm tipping frame for extended downwards profiling. (a,b) The lowered arm in normal orientation, reaching down approximately 100 cm below horizontal. (c,d) The tipped frame pivoted about the furthest rung, with the arm straight relative to the frame. The profiling range increases by an additional 150 cm downwards.

S1.2 Campaign location

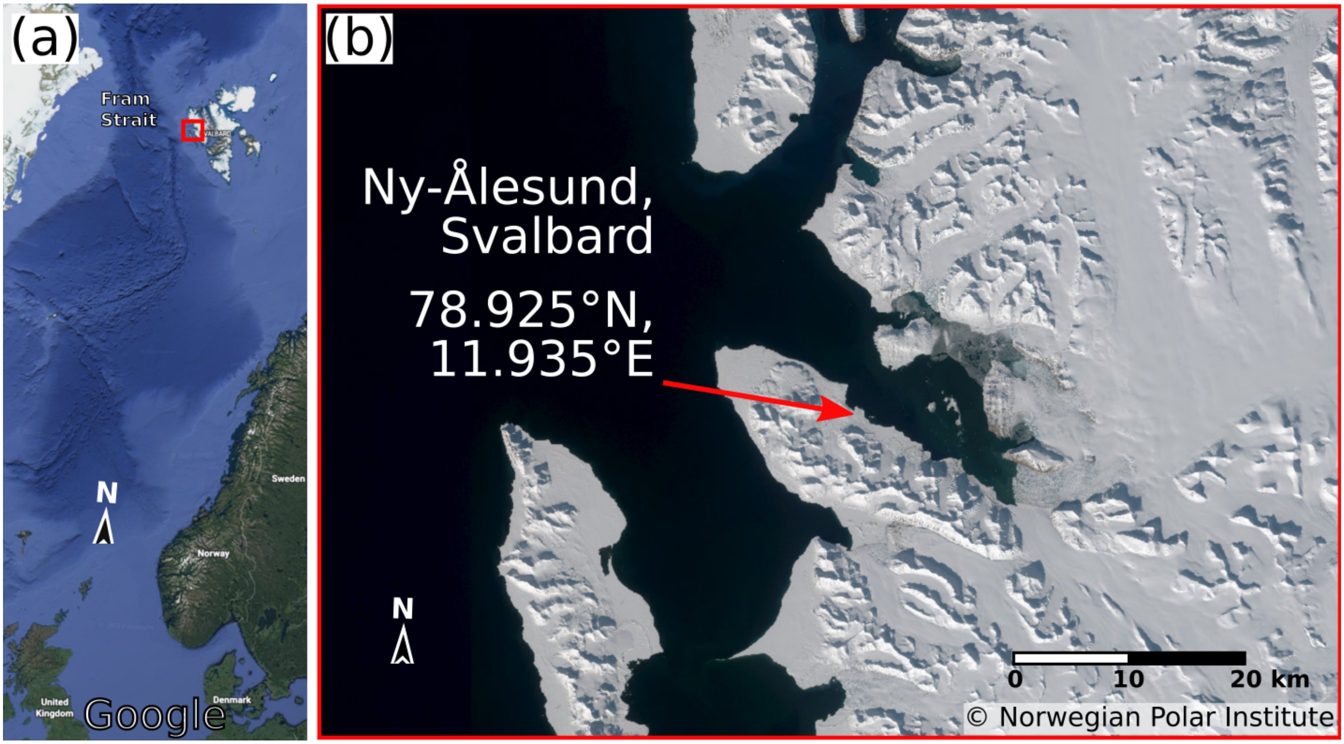

Figure S2. (a) Location of Svalbard and campaign area (red square) (© Google Earth 2022). (b) Zoom in on the campaign area showing the location of Ny-Ålesund on the southern shore of Kongsfjorden (© Norwegian Polar Institute, http://toposvalbard.npolar.no).

S1.3 T_{DAS} and T_{WB} relationship

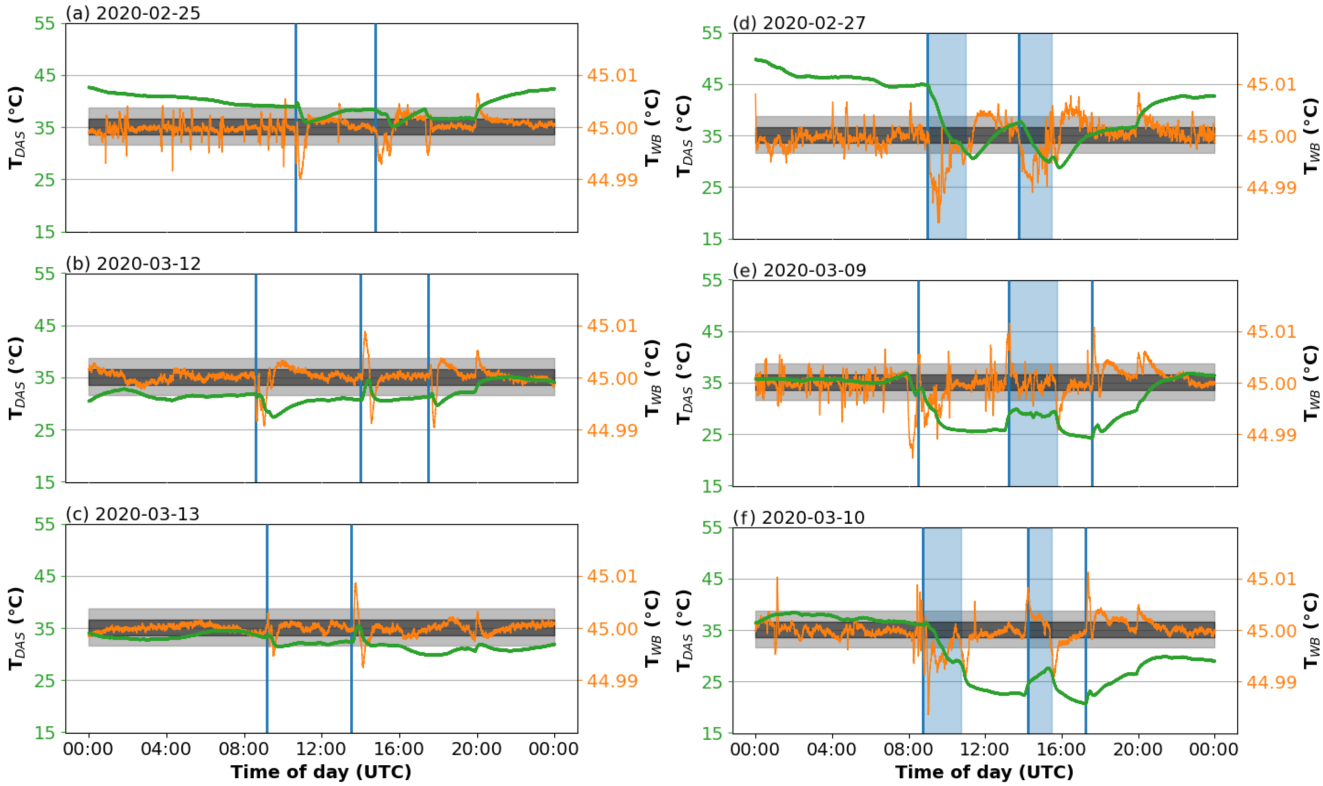

Figure S3. Daily timeseries of DAS temperature (left axis, green) and Warm Box temperature (right axis, orange) on (a) 25 Feb 2020, (b) 12 Mar 2020, (c) 13 Mar 2020, (d) 27 Feb 2020, (e) 9 Mar 2020, and (f) 10 Mar 2020. Black shading denotes spread between 2nd and 98th percentiles of Warm Box temperatures during laboratory benchmark. Gray shading indicates the same, for the deployment period in the Zeppelin Observatory. Blue lines are brief site visits, lasting on the order of 5 to 10 minutes. Blue shading indicates profiling periods, where the ISE-CUBEs were attended with the cover removed.

Increases or decreases in T_{DAS} had a tendency to coincide with sudden dips or spikes in T_{WB} (Figure S3). While the impact of T_{DAS} perturbations could last up to around 4 hours, T_{WB} instability was shorter lived, usually returning to benchmark values within an hour. However, the magnitude of these perturbations, and the subsequent recovery time, is largely related to the kind of operation prompting the disturbance. Brief site visits (Figure S3, blue lines), such as routine checks or swapping Cold Trap collection vials, would produce a relatively small change in T_{DAS}, as compared to longer operations (Figure S3, blue shading), such as profiling. Accordingly, recovery time for the T_{WB} would also be longer during the profiling periods, though the magnitude of the T_{WB} dip/spike is independent of site visit type.

S1.4 Sample transmission at Snow

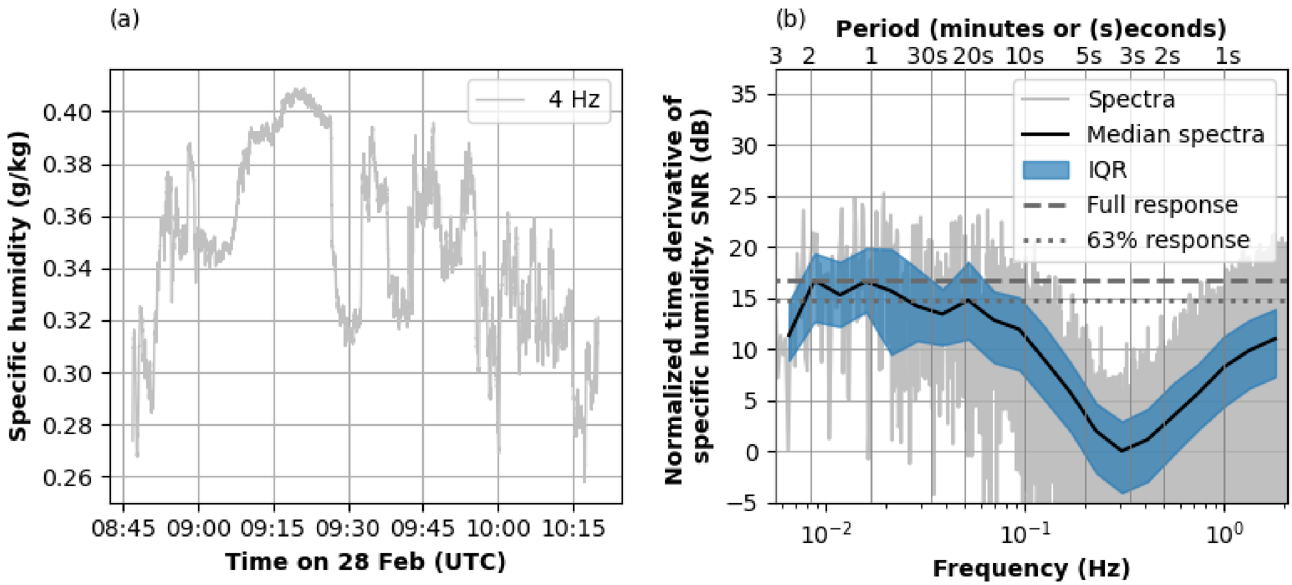

Figure S4. Inlet response determination for the profiling period on 28 Feb 2020, from 8:47 to 10:20 UTC. (a) The 4 Hz specific humidity signal as measured by the analyzer. (b) The fast Fourier transform of the normalized time derivative of the specific humidity (gray), expressed as a signal to noise ratio. Black line is the median of the resulting power spectra, across 20 logarithmically spaced bins between between $5.55x10^{-3}$ and 2 Hz, while colored shading is the interquartile range (IQR) of the bin. The minimum of the median (at approximately 0.4 Hz or 2.5 s) serves as the noise baseline, whereas the maximum signifies the full response (dashed gray line). Dotted line indicates 63% of the full response.

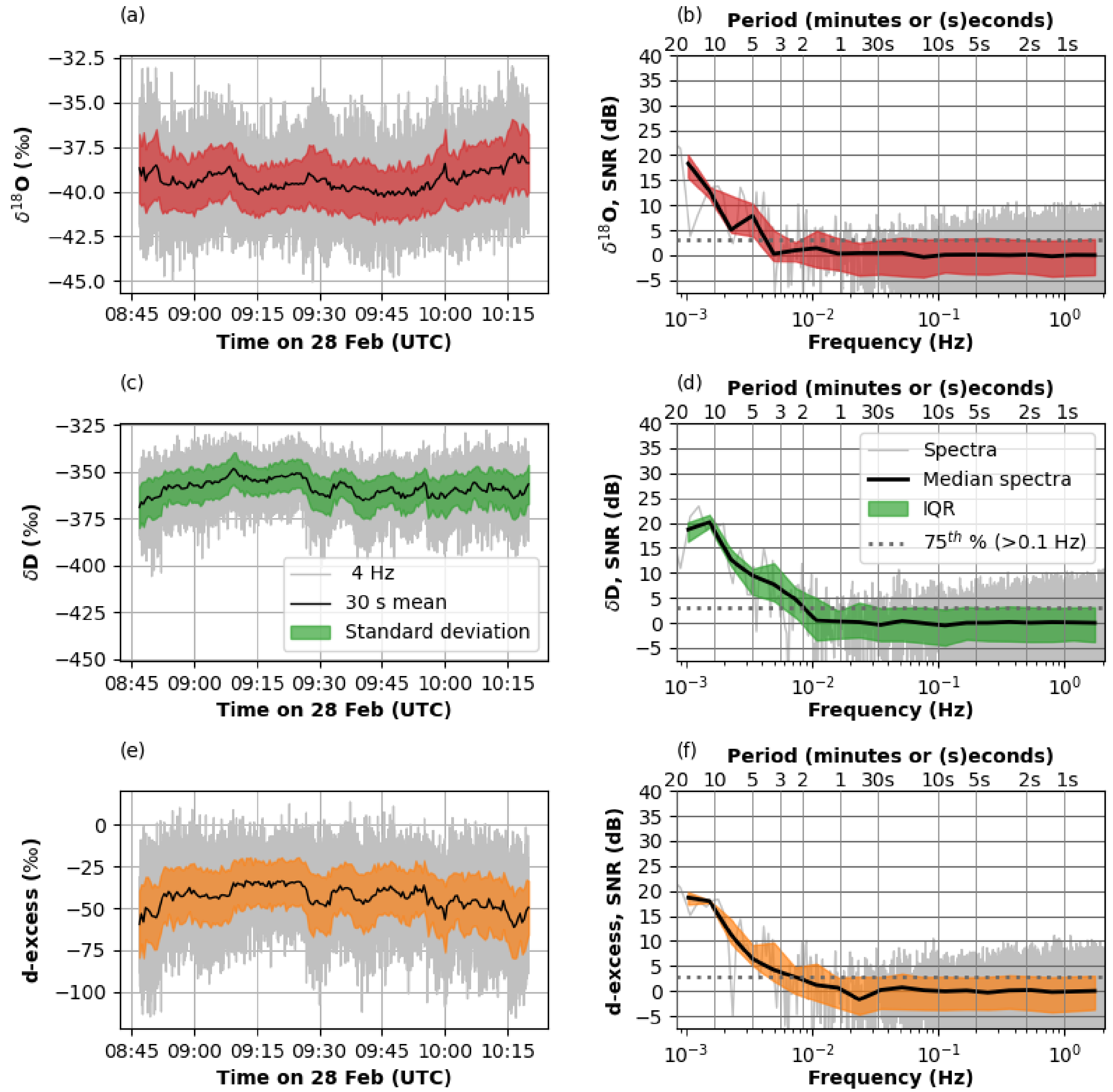

Figure S5. Resolving isotopic signals during the profiling period on 28 Feb 2020, from 8:47 to 10:20 UTC. (a) The 4 Hz δ^{18}O signal (gray), with the 30 s mean (thick black) and standard deviation of the same (colored shading). (b) The fast Fourier transform of δ^{18}O (gray), expressed as a signal to noise ratio. Black line is the median of the resulting power spectra, across 20 logarithmically spaced bins between between $8.33\text{x}10^{-4}$ and 2 Hz, while colored shading is the interquartile range (IQR) of the bin. (c,d) Same as a,b), but for δD. (e,f) Same as a,b), but for d-excess. Dotted line is the mean of the 75th percentile for frequencies larger than 0.1 Hz

S2 ISE-CUBE templates and 3D models

To make the holes for the electrical and pneumatic connectors, we used an off-site laser cutting service to fashion wooden templates from the "ISE_CUBES-connectors_template.svg" file. If laser-cutting service is unavailable, a large printer (accommodating at least A2 paper) can produce initial paper templates (using "ISE_CUBES-connectors_template.pdf") that can then be transferred over to a sturdier medium (e.g. thin plywood). We would not recommend directly using paper templates on the plastic cases. The sturdy templates then fit on the plastic case as shown in Figure S6. Once the template is mounted and secured with tape, the outline of each individual connector can be transferred onto the plastic. After etching, the template may or may not need to be removed, depending on the tools available to make the holes. We would recommend a power drill and hole saw set for the initial holes, and then hand tools to finish. This process should be taken slowly and iteratively, as it is crucial that the holes not be so large as to allow the connectors to turn during fastening. The exact model numbers of connectors used/recommended can be found in Sect. S2.1.

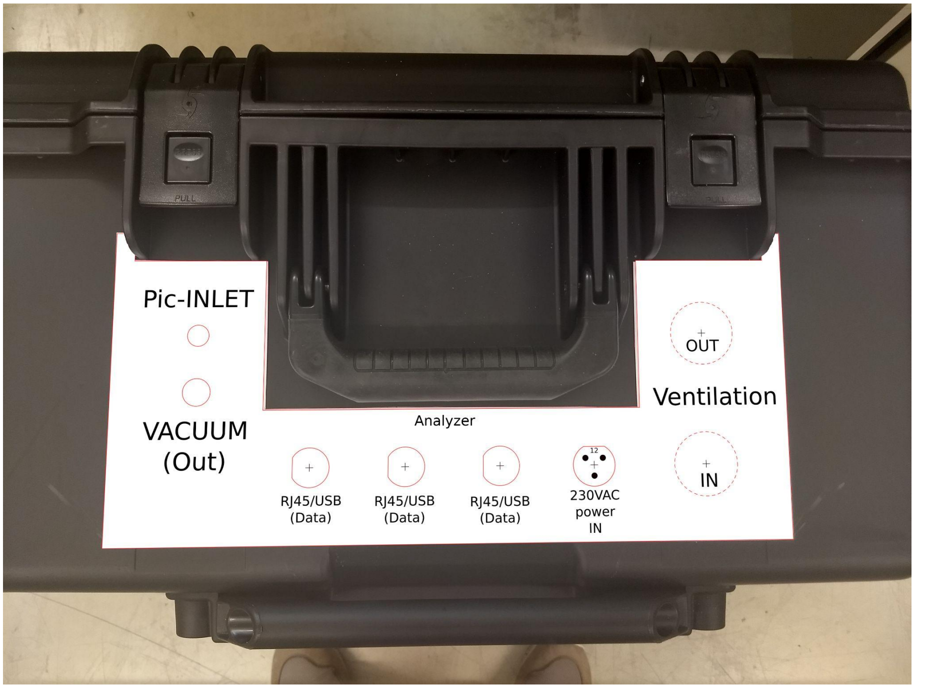

Figure S6. Example of the connector template on the Analyzer module. Please note that this is for illustration purposes, and the actual template should be made with something sturdier than paper.

The "ISE_CUBES-connectors_template" files have three large templates, one for each large ISE-CUBE module. Also included are smaller support plates that will help keep the pneumatic connectors in place. Though our prototype system had a separate small case for the Profiling module, we would recommend combining it with the Cold Trap module. In this way, the same Arduino Mega microcontroller can manage data streams for both the Cold Trap and Profiling modules.

Ventilation holes on the templates are given as guides and should be tailored to the exact ventilation system that one would utilize. However, they are the correct size to accommodate a 1 inch BSP-threaded cam and groove adapter (362-6813, RS PRO); see below. We would recommend integrating a more powerful, dedicated Ventilation module into the system that would allow for deployments in warmer environments. After our field deployment, we had promising test results with a simple plastic storage container and a 209 m^3/hour blower fan (RG160-28/14NU, ebm-papst) in ambient temperatures up to 19℃. Nevertheless, we provide the "ISE_CUBEs-blower_fan_mount.stl" file that can be used to 3D print the original ventilation mount for the ebm-papst RL90-18/56 blower fan used in 2020. The fan attaches to the mount with two M4x25mm socket screws. The mount is then placed inside the plastic container in the middle of the connector sidewall (Figure S7, left panel). The mount is kept in place when the 1 inch BSP-threaded cam and groove adapter (Figure S7, right panel) is threaded through the plastic container hole; once correctly placed, double sided tape on the backside of the mount can help ensure that the fan assembly does not move. The corresponding cam and groove coupler (362-6712, RS PRO) can be attached to guide ventilation flow with flexible ducting (9110030250000, Merlett Plastics).

Figure S7. (Left panel) Placement of the original ventilation fan and mount. (Right panel) Cam and groove adapter with connected cam and groove coupler and ducting below.

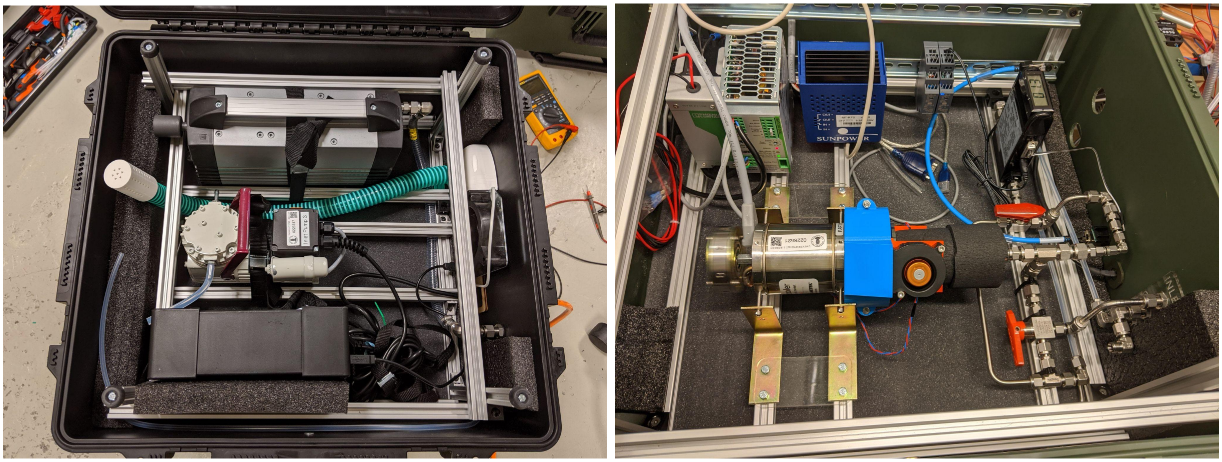

Figure S8. Left panel: Interior of Pump module with aluminium support frame. Right: An early iteration of the Cold Trap module interior with the aluminium frame.

The frames for Pump and Cold Trap modules used Rat-Rig aluminium profiles (Figure S8), with rubber pads at the end. The pad/profile lengths were cut to exactly fit the interior height of the plastic case, thereby "sandwiching" the frame between main case and lid. Ventilation mountings for the cryocooler are model and configuration specific and are not provided in this Supplement.

One might consider including a Raspberry Pi computer in the Cold Trap module, in addition to the Arduino Mega microcontroller. With a Raspberry Pi, one could more readily monitor and control the cryocooler over serial connection. And as we would recommend replacing the "(low range) mass flow meter and needle valve" combination with a mass flow controller, the Raspberry Pi would allow for the user to regulate the controller remotely. The Raspberry Pi could also expand capabilities for the integrated Profiling module, as will be discussed in Sect. S2.2. As the Arduino code depends on libraries and the exact instrumentation used in the module used, it is not included in this Supplement.

S2.1 ISE-CUBE component list, by module

While major/critical components are accounted for, the lists that follow are not exhaustive. In order to optimize any attempts to recreate the system, these lists utilize many of the suggestions made above. Namely, integrating the Profiling module datalogging into the Cold Trap container, replacing the mass flow meter/needle valve combination with a mass flow controller, and adding a Raspberry Pi. System costs also do not account for the cost of the CRDS analyzer or CRDS vacuum pump. Calculated costs/lists do include the cost of having a 12/24 VDC output in the Pump module (Table S2) for an external ventilation system.

Due to supply and time constraints, our system used the same, smaller circular connectors (Table S2, 62GB-57A08-33SN) for power output to the Analyzer and Profiling modules, with 230 VAC and 12 VDC, respectively. As this introduces the potential for instrument damage due to connection mix-up, we recommend changing the 230 VAC connectors to be consistent with the larger 230 VAC connectors (Table S1 and S2, 62GB-57A12-03PN and 62GB-57A12-03SN). This recommended change is also present in the "ISE_CUBES-connectors_template" in the attached files and in the following tables.

Similarly, we used the same cable (Alpha Wire EcoFlex, 79002 SL005) for DC power and Profiling module data (Table S5). A shielded cable (Lapp, 34063, or similar) would fit better for data transmission to the Profiling module, as we noticed a noisier signal when the Profiling module data cable was coiled.

As the circular connectors are a not-insignificant contributor to the cost of the system, using more cost effective alternatives would be a natural place to start. For example, the RS PRO 21-mm series of electrical connectors could replace Amphenol LTD brand connectors, though templates would have to be modified.

Vacuum bulkheads used in the ISE-CUBE modules (SS-600-61 and SS-400-61, Swagelok Inc.) should utilize silicone rubber O-rings with inner diameters of 12 (SS-400-61) and 15 (SS-600-61) mm on either side of the plastic container to ensure a good seal.

S2.1.1 Analyzer module

Table S1. Analyzer module components. *Cost of the CRDS analyzer is excluded from total costs

Component	Manufacturer: Model	Number used	Approximate cost, total (EUR)
Container	Pelican Products Inc.: iM2875 Storm	1	400
CRDS Analyzer	Picarro Inc.: L-2130i	1	-
230 VAC power IN, bulkhead	Amphenol LTD: 62GB-57A12-03PN	1	50
230 VAC power IN, cable	Amphenol LTD: 62GB-16J12-03SN	1	130
USB connectors	RS PRO: 111-6759	2	60
RJ45 connector	Amphenol Socapex: RJ45F7RJ	1	25
RJ45 circular connector cable	Amphenol Socapex: RJ45F6200OPEN	1	30
USB-A/USB-A (interior cables)	RS PRO: 182-8855	2	10

RJ45 (interior cable)	Omron: XS6W-6LSZH8SS30CM-B	1	15
Ventilation fan	Ebm-papst GmbH & Co. KG: RL 90-18/56	1	70
Vacuum bulkhead	Swagelok Inc: SS-600-61	1	100
Inlet bulkhead	Swagelok Inc: SS-400-61	1	100
One-way check valve	Swagelok Inc: 6L-CW4S4	1	100
90° elbow (¼ inch)	Swagelok Inc: SS-400-2R-4	2	80
90° elbow (⅜ inch)	Swagelok Inc: SS-600-2R-6	2	60
Ventilation bulkhead	RS-PRO: 362-6813	2	20
Ventilation connector	RS-PRO: 362-6712	2	30
		Total	**1320**

S2.1.2 Pump module

Table S2. Pump module components. *Costs for 12/24 VDC output

Component	Manufacturer: Model	Number used	Approximate cost, total (EUR)
Container	Pelican Products Inc.: iM2875 Storm	1	400
CRDS vacuum pump	KNF DAC GmbH.: N920AP.29.18	1	-
Inlet vacuum pump (shared with Cold Trap)	KNF DAC GmbH.: N022AN.18	1	500
UPS	Eaton: EL500FR	1	100
Aluminium frame (kit)	RatRig: HW1142GK	1	100

230 VAC power IN	Amphenol LTD: 62GB-57A12-03PN	1	50
230 VAC power IN, cable	Amphenol LTD: 62GB-16J12-03SN	1	130
12/24 VDC power OUT, bulkhead*	Amphenol LTD: 62GB-57A08-33SN	1	40
12/24 VDC power OUT, cable*	Amphenol LTD: 62GB-16J08-33PN	1	70
230 VAC power OUT, bulkhead	Amphenol LTD: 62GB-57A12-03SN	1	40
230 VAC power OUT, cable	Amphenol LTD: 62GB-16J12-03PN	1	170
USB connector	RS PRO: 111-6759	1	30
USB-A/USB-A (interior cables)	RS PRO: 182-8855	1	5
Ventilation fan	Ebm-papst GmbH & Co. KG: RL 90-18/56	1	70
Vacuum bulkhead	Swagelok Inc: SS-600-61	1	100
Inlet bulkhead	Swagelok Inc: SS-400-61	1	100
230 VAC to 12/24 VDC Adapter*	MeanWell: GST18E12-P1J or GST18E24-P1J	1	35
Ventilation bulkhead	RS-PRO: 362-6813	2	20
Ventilation connector	RS-PRO: 362-6712	2	30
		Total	**1990**

S2.1.3 Profiling module (integrated into Cold Trap expansion container)

Table S3. Profiling module components. *Including parts and fabrication

Component	Manufacturer: Model	Number used	Approximate cost, total (EUR)
Aluminium arm and tipping frame	Custom made	1	2 000*
Steel tripod	Campbell Scientific: CM110	1	1 000
Steel mount for arm	Custom made	1	100*
5 VDC OUT & Data, bulkhead	Amphenol LTD: 62GB-57A12-10SN	1	75
5 VDC OUT & Data, cable	Amphenol LTD: 62GB-16J12-10PN	1	120
230 VAC to 12 VDC Adapter	MeanWell: GST18E12-P1J	1	35
Single board computer	Raspberry Pi: 3 B+	1	50
Microcontroller (shared with Cold Trap)	Arduino: MEGA	1	30
SD card shield (shared with Cold Trap)	Seeed studio, 103030005	1	20
Real-time clock (shared with Cold Trap)	Seeed studio, 101020013	1	10
OLED display (shared with Cold Trap)	Adafruit: 326	1	30
Ultrasonic distance sensors	SparkFun Elec.: SEN-15569	2	10
Temperature sensor	Velleman: VMA324	1	15
		Total	**3495**

S2.1.4 Cold Trap expansion module (with integrated Profiling module)

Table S4. Cold Trap expansion module components.

Component	Manufacturer: Model	Number used	Approximate cost, total (EUR)
Container	Pelican Products Inc.: iM2875 Storm	1	400
Cryocooler (including controller and accessories)	Sunpower: Cryotel MT	1	20 000
Mass flow controller	Aalborg: GFC17S-VAL6-A0	1	1 500
Power supply/UPS (24 VDC)	Phoenix Contact: 2866611	1	450
Aluminium frame (kit)	RatRig: HW1142GK	1	100
230 VAC power IN	Amphenol LTD: 62GB-57A12-03PN	1	50
230 VAC power IN, cable	Amphenol LTD: 62GB-16J12-03SN	1	130
USB connector	RS PRO: 111-6759	1	30
Ventilation fan	Ebm-papst GmbH & Co. KG: RL 90-18/56	1	70
Cryocooler ventilation fans	Ebm-papst GmbH & Co. KG: RLF35-8/14N	2	100
Inlet & Exhaust bulkheads	Swagelok Inc: SS-400-61	2	200
One-way check valve	Swagelok Inc: 6L-CW4S4	1	100
Reducer (⅜ to ¼ inch)	Swagelok Inc: SS-600-R-4	1	15
90° union elbow (⅜ inch)	Swagelok Inc: SS-600-9	1	30

Union tee (⅜ inch)	Swagelok Inc: SS-600-3	1	30
Port connector (⅜ inch)	Swagelok Inc: SS-601-PC	3	30
Reducing union, bore-thru (⅜ to ⅛ inch)	Swagelok Inc: SS-600-6-2BT	1	20
Tube Adapter (⅜ to ⅛ inch)	Swagelok Inc: SS-6-HC-A-601	1	20
Ventilation bulkhead	RS-PRO: 362-6813	2	20
Ventilation connector	RS-PRO: 362-6712	2	30
		Total	**23 225**

S2.1.5 Cabling and ducting

Table S5. Various cables and ducting used in the system. *Used with 62GB-16J08 connectors (DC Power). **Used with 62GB-16J12 connectors (Data).

Component	Manufacturer: Model	Amount	Approximate cost, total (EUR)
Mains power (230 VAC)	Lapp: 0013631	50 m	350
DC power*	Alpha Wire EcoFlex: 79002 SL005	31 m	300
Data cable, shielded (5 pair)**	Lapp: 34063	50 m	350
Flexible Ducting	Merlett Plastics: 9110030250000	25 m	150
		Total	**1 150**

S2.2 Profiling arm drawings and 3D models

We used a 65 mm outer diameter (OD) aluminium pipe, with 2.5 mm thick walls as the basis for our articulating arm. For this diameter and weight of pipe, we required a custom-made mounting adapter (“Profiling-Steel_mount” files). As constructing this adaptor was non-trivial, we would recommend using a narrower pipe, with thinner walls. With a pipe smaller than 38 mm OD, one could use the CM210 Crossarm-to-Pole Bracket from Campbell Scientific, which is designed to attach to our chosen tripod (CM110, Campbell Scientific). Therefore, both the articulating arm and the upper cross-arm could use these commercially available brackets. Two small pulleys are attached to the end of the upper cross-arm

The head of the profiling arm was kept parallel with the ground with four guiding steel wires, attached above (two) and below (two) the main body of the arm ("Profiling-arm_drawings.pdf"). We made two pivot points in the ¼ inch stainless steel tubing with 5 cm lengths of ¼ inch PTFE tubing at the appropriate positions (Figure S9).

Figure S9. The head (left panel) and base (right panel) sections of the interior tubing of the profiling arm, including two 5 cm PTFE lengths.

We include the "Profiling-sensor_head" files, which contain slightly modified models of the sensor head housing we used, though still using all the same sensors as were used in 2020. The most substantial physical change is that the sensor head now mounts directly to the head of the arm, with multiple cable ties and/or long hose clamps (Figure S10). Additionally, the temperature sensor now has a naturally ventilated radiation shield. Two cable ties are also used to attach the main box and lid; similarly, two cable ties are also used to attach the temperature sensor to the mount and one to attach the shield to the mount. The temperature sensor cable is fed into the main box through an M12 cable gland at the rear of the main box. The main umbilical (leading to the Profiling module case/Arduino) is passed through an M20 cable gland. Rubber O-ring gaskets are used to seal ultrasonic mounts and the main box lid. As the Arduino code depends on libraries and the exact sensor models used, it is not included in this Supplement.

Though we include these models for completeness, in light of the deficiencies encountered with our chosen ultrasonic distance sensors (during windy and low-level snowpack operations), we would recommend replacing them. Potential replacements could be either higher quality ultrasonic sensors or Time of Flight LiDARs, such as the Teraranger Evo series from Terabee. An additional advantage of these particular LiDARs is that they come with USB 2.0 interfaces, allowing for direct connection and logging to the Analyzer module. However, if one includes a Raspberry Pi computer in the ColdTrap/Profiling module (as discussed in Sect. S2.1), it would be possible to route the USB connection to that module, rather than tasking the CRDS analyzer with more datalogging. In any case, replacing the distance sensors would involve redesigning the sensor box.

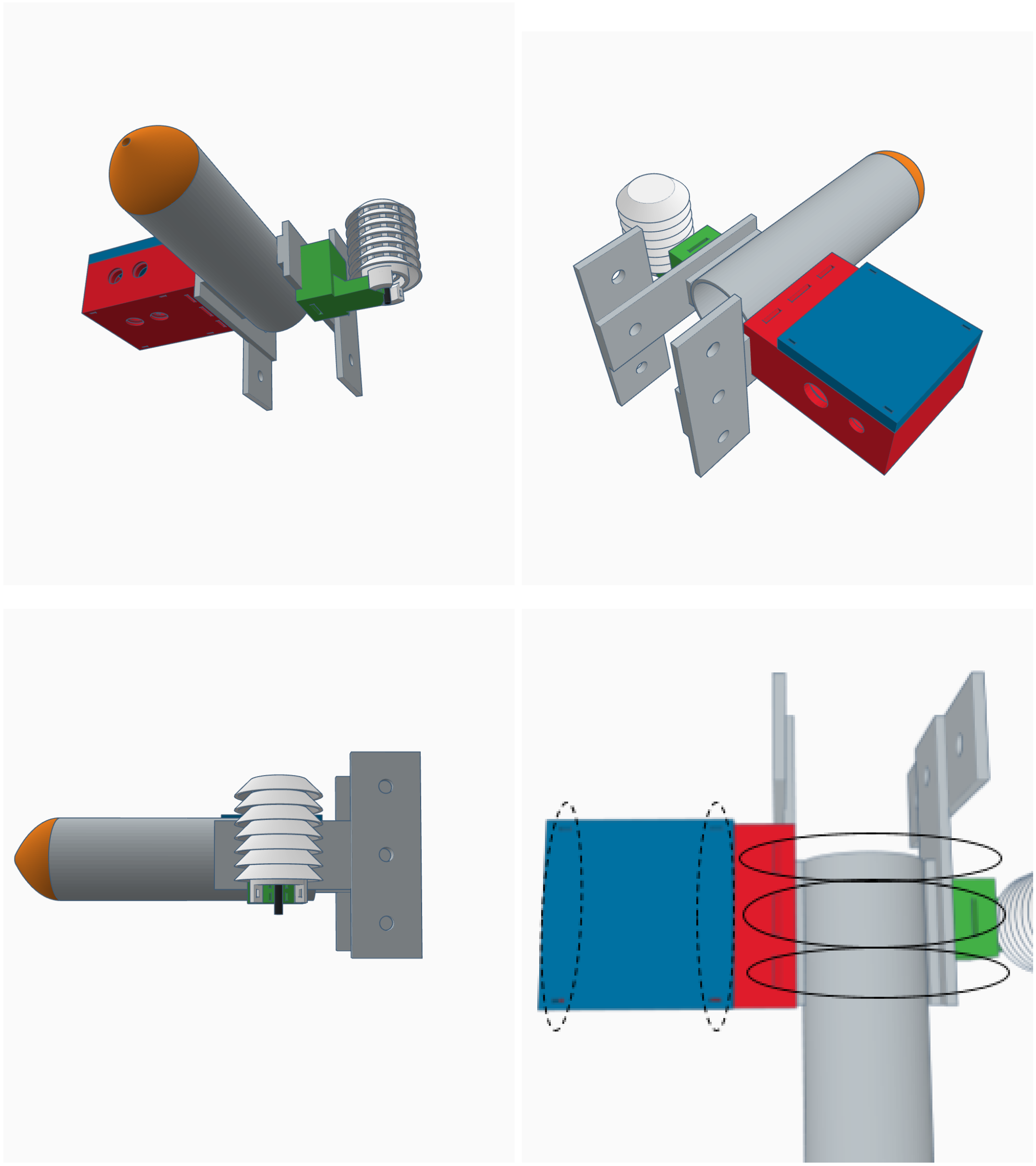

Figure S10. The redesigned sensor package. Main box (red) attaches to the arm head (gray) with cable ties and/or long hose clamps through three slots, also securing the temperature sensor mount (green) (lower right panel, solid ellipses). Lid (blue) attaches to the main box with two long cable ties (lower right panel, dashed ellipses). Temperature shield attaches to the mount with a cable tie (lower left panel). Head cap (orange) slides into tubing and is secured with adhesive tape.